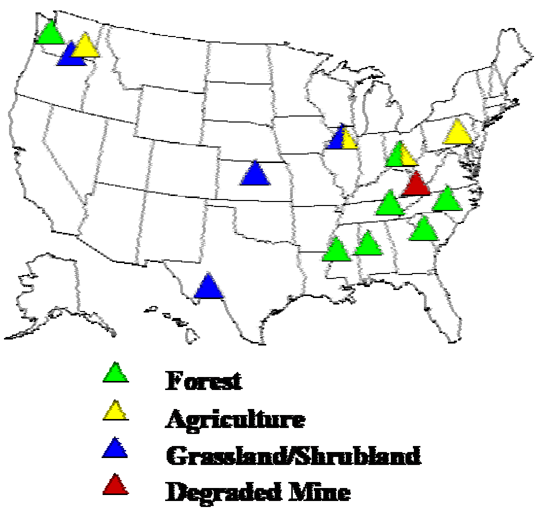
DOE Consortium for Research on ***Enhancing***

Carbon
Sequestration
in
Terrestrial
Ecosystems



CSiTE is a research consortium

DOE National Laboratories

Argonne National Laboratory
Oak Ridge National Laboratory
Pacific Northwest National Laboratory

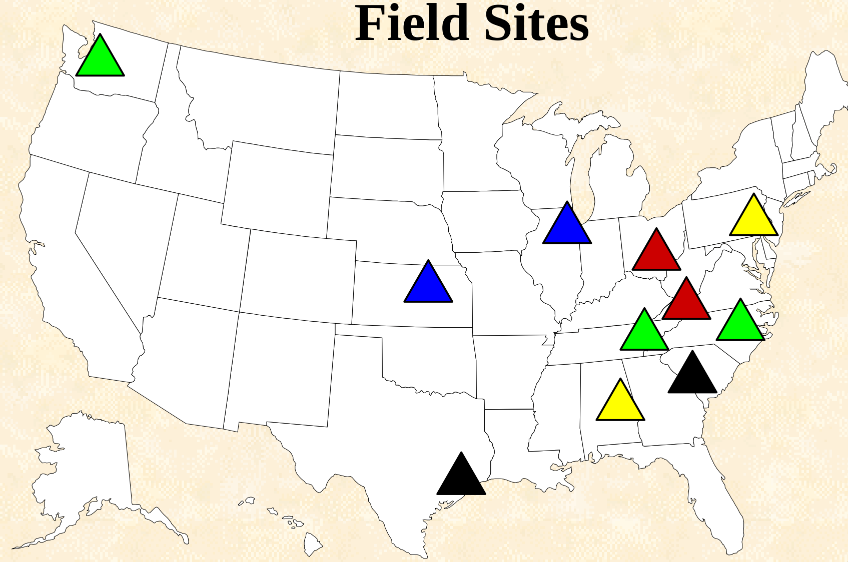
Research Institutions

Joanneum Inst for Energy Res, Austria
USDA Center for Forested Wetlands Res, SC
USDA Land Mgmt & Water Cons Unit, WA
USDA Nat Soil Dynamics Lab, AL
USDA Nat Soil Tilth Lab, IA

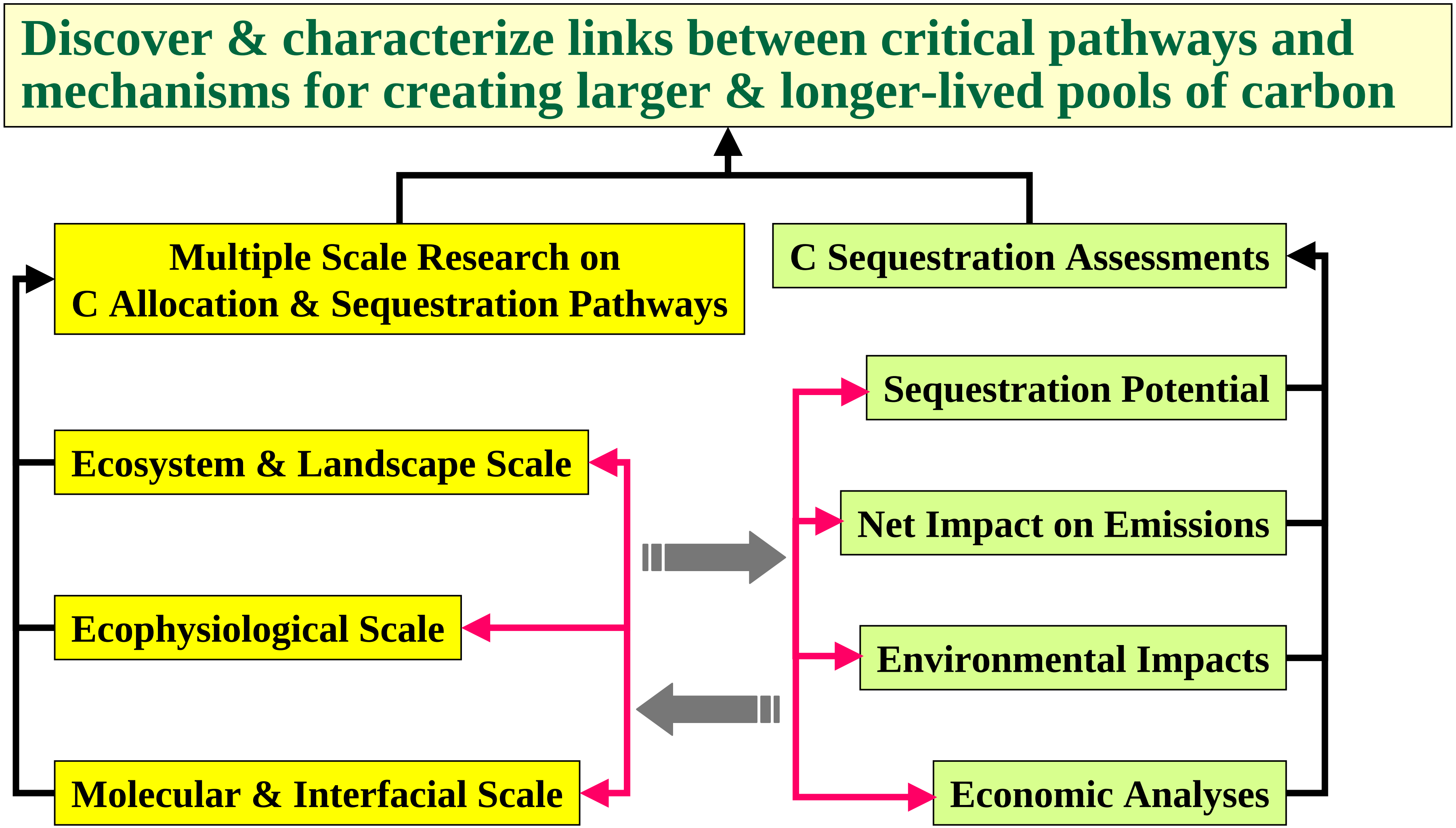
Universities

Colorado State University
Cornell University
North Carolina State University
Ohio State University
Texas A&M University
University of Washington

Field Sites

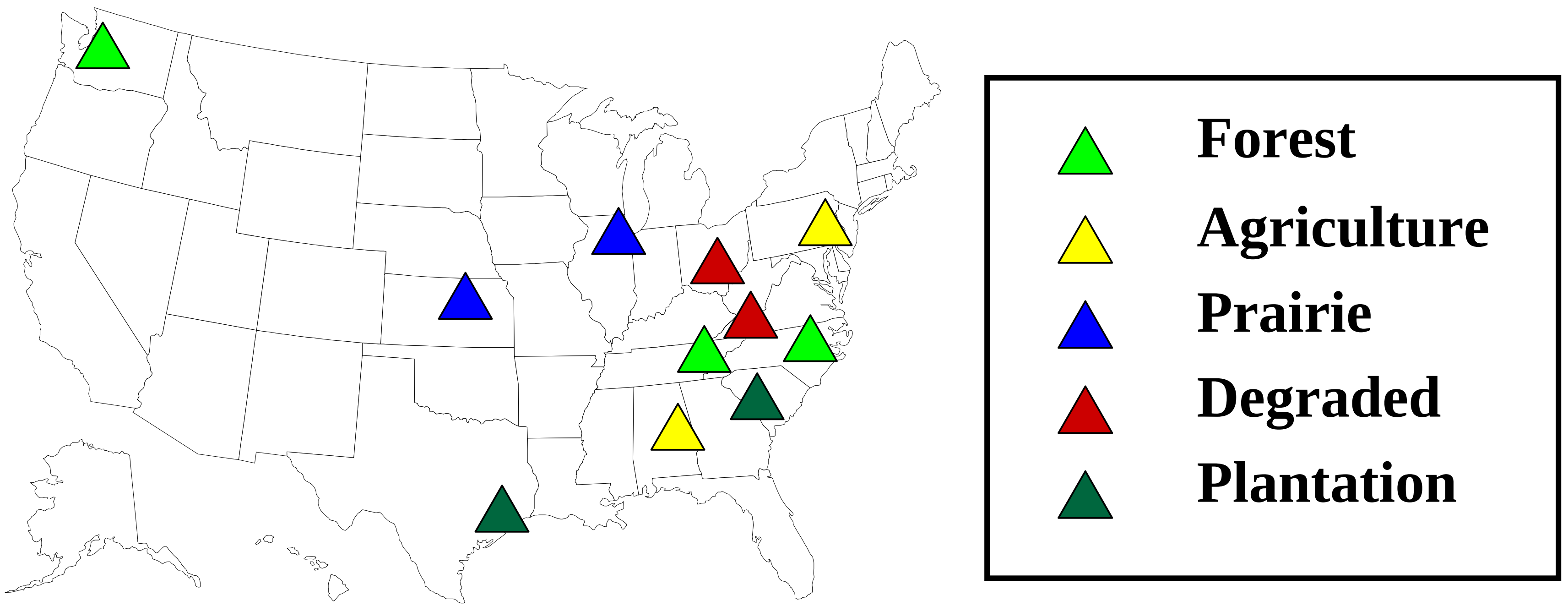


Science-based understanding to support development and assessment of strategies for carbon sequestration in terrestrial ecosystems



Use existing opportunities:

Sites where long-term applications of alternative practices are already established, or are being established for other reasons



Multiple ecosystems subjected to a variety of land uses or management practices

What is carbon sequestration?

- **Keep anthropogenic CO_2 emissions from reaching the atmosphere**
  - Capture
  - Isolate
  - Divert to secure storage
    - Geological injection
    - Ocean injection
    - Carbonate minerals
- **Remove CO_2 from the atmosphere**
  - Natural systems
    - Vegetation & soil
    - Oceans
  - Engineered systems
    - Mineral carbonation
    - Algal ponds

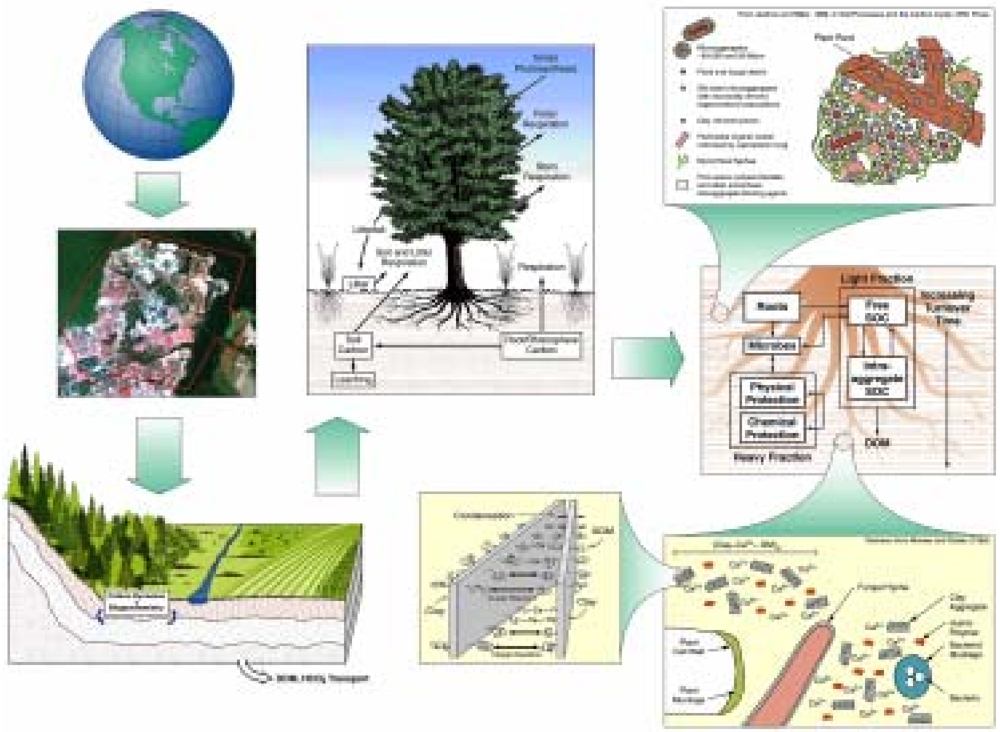
Viability tests
- Safe
- Environmentally benign
- Effective
- Economical
- Acceptable to public

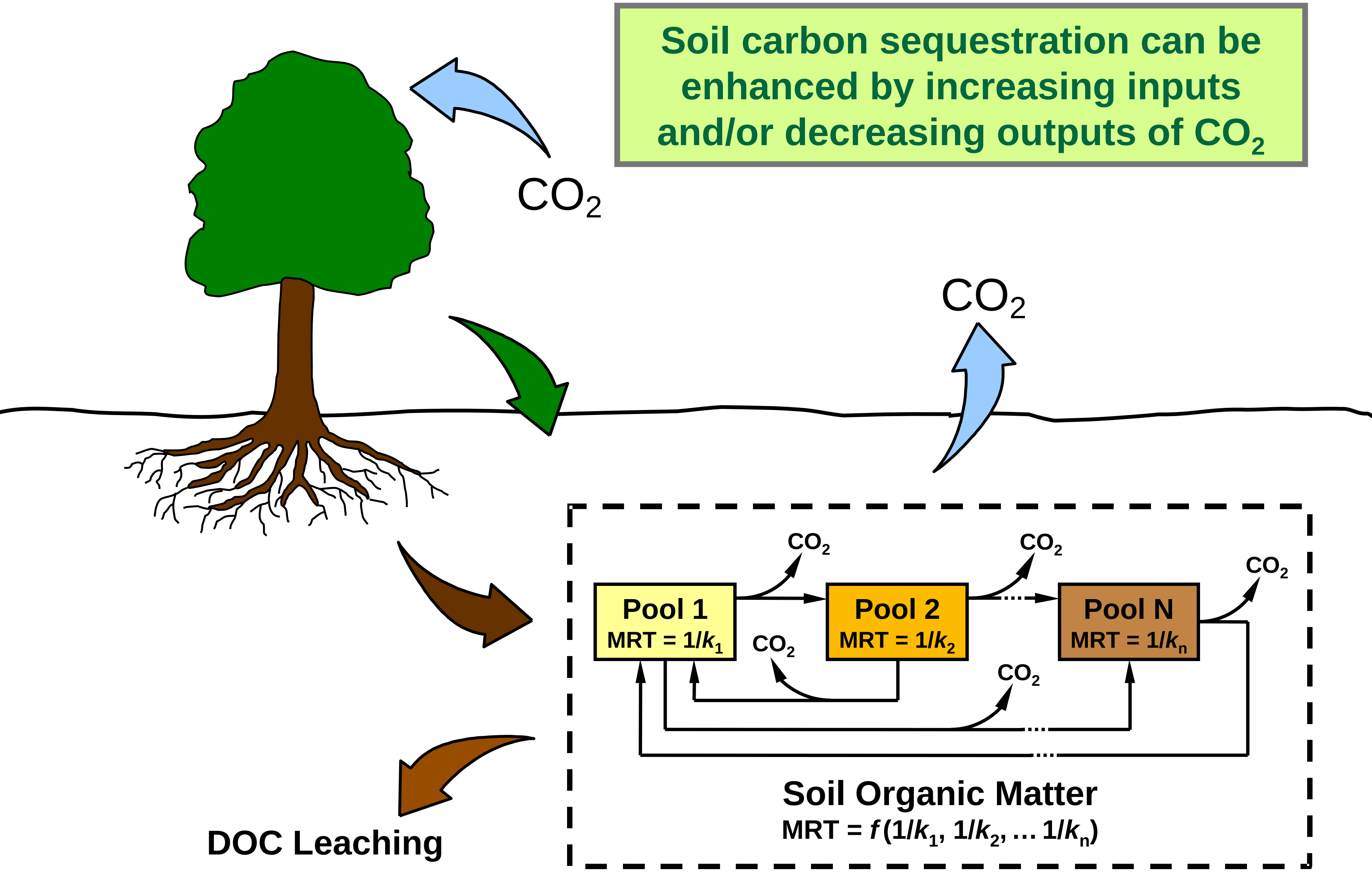
CSiTE Mission
Fundamental science supporting approaches for enhanced sequestration

Soil carbon focus within context of whole ecosystems

- ❶ **Discover how to alter carbon capture and sequestration mechanisms from molecular to landscape scales**
- ❷ **Develop conceptual and simulation models for extrapolation across spatial and temporal scales**
- ❸ **Advance science of assessing environmental and economic consequences of sequestration**

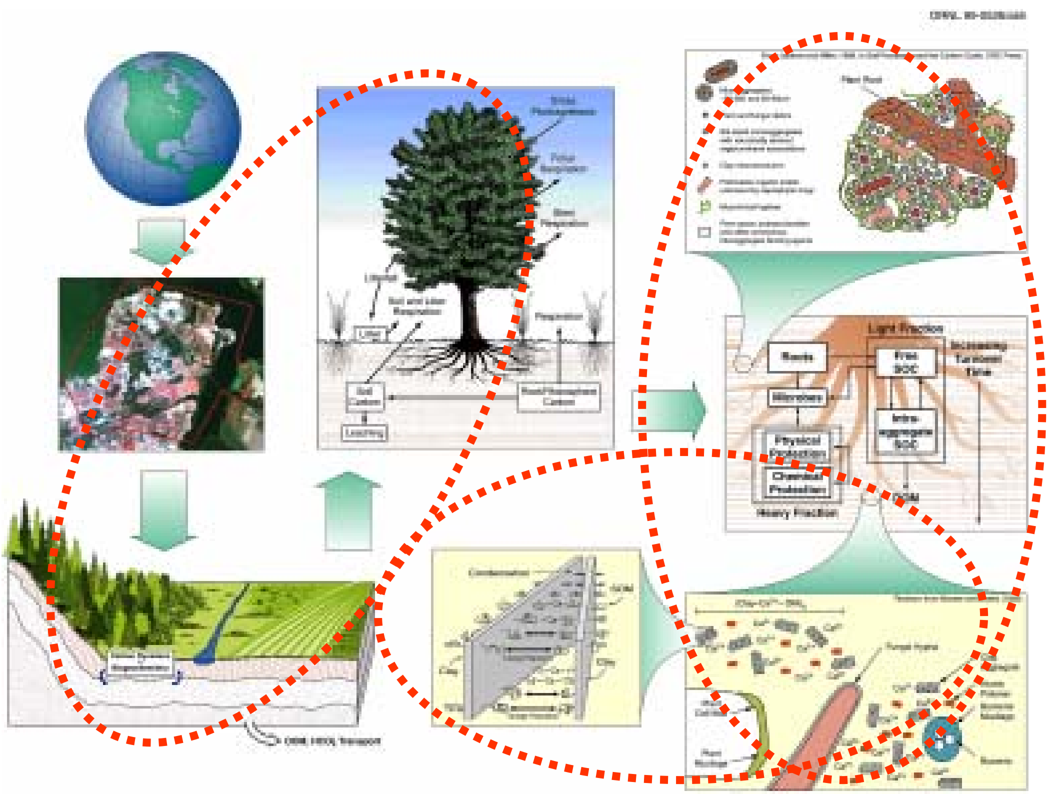
Multi-scale & multi-disciplinary




Soil carbon sequestration can be enhanced by increasing inputs and/or decreasing outputs of CO_2
CO_2
CO_2
CO_2
CO_2
CO_2
Pool 1
MRT = $1/k_1$
CO_2
Pool 2
MRT = $1/k_2$
CO_2
Pool N
MRT = $1/k_n$
Soil Organic Matter
MRT = $f\,(1/k_1,\ 1/k_2, \ldots\ 1/k_n)$
DOC Leaching

What's are some possible options to enhance carbon sequestration?

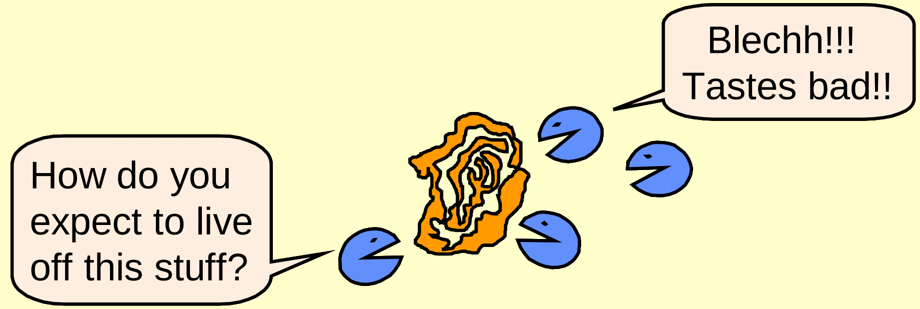
- **Alter inputs (litter), root density, depth, chemistry**
  - **Manage vegetation, alter cultivars**
  - **Fertilization, moisture, etc.**
- **Shift decomposition rates and products**
  - **Shift structure and function of microbial communities**
  - **Modify chemistry**
- **Optimize physicochemical conditions**
  - **Physical/chemical protection**
  - **Humification redox reactions**
  - **Promote deeper transport of C**



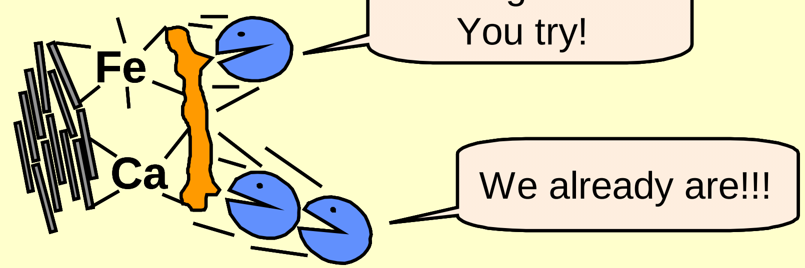
MECHANISMS OF SOIL ORGANIC MATTER STABILIZATION

From Jastrow and Miller, 1998, *In* Soil Processes and the Carbon Cycle, CRC Press.

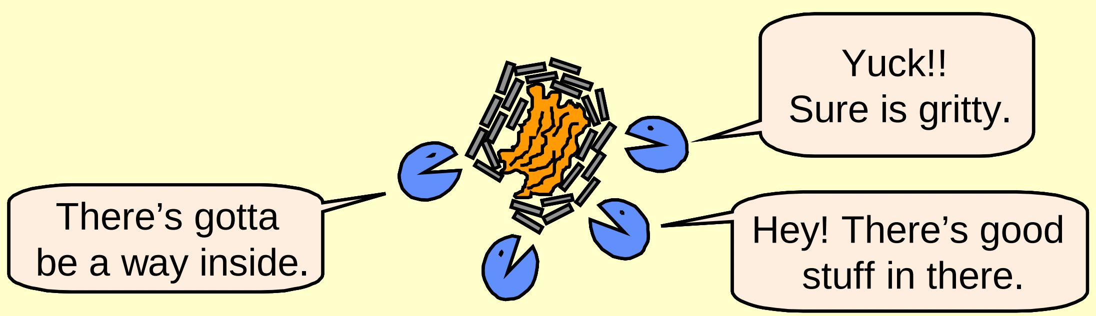
Biochemical Recalcitrance



Chemical Stabilization

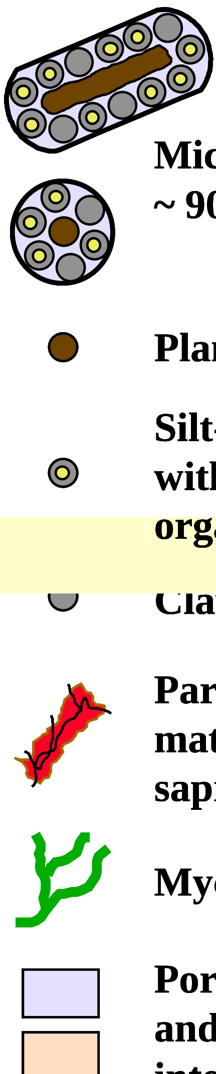


Physical Protection



CONCEPTUAL DIAGRAM OF AGGREGATE HIERARCHY

From Jastrow and Miller, 1998, *In* Soil Processes and the Carbon Cycle, CRC Press.



Microaggregates
~ 90-250 and 20-90 μm

Plant and fungal debris

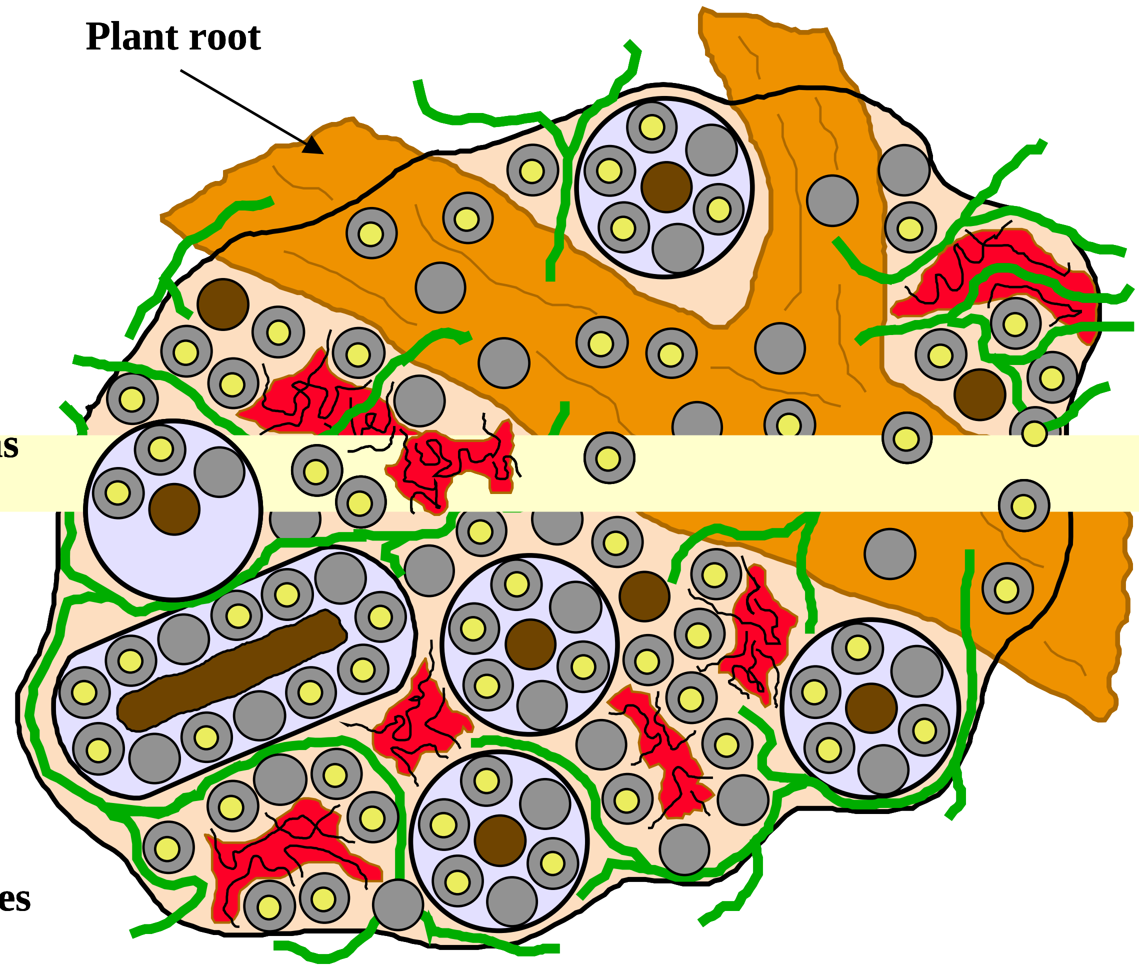
Silt-sized microaggregates with microbially derived organomineral associations

Clay microstructures

Particulate organic matter colonized by saprophytic fungi

Mycorrhizal hyphae

Pore space; polysaccharides and other amorphous interaggregate binding agents



Look at all the carbon stuck in there!!

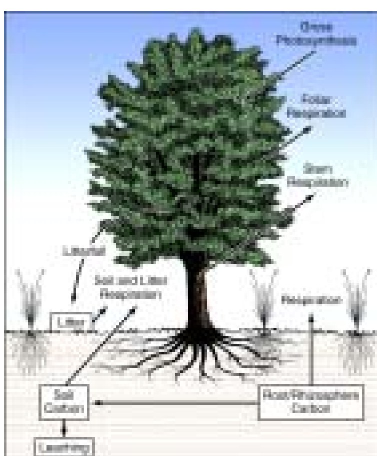
Conversion of Croplands to Grassland: Understanding carbon sequestration dynamics, potentials, and mechanisms at multiple scales

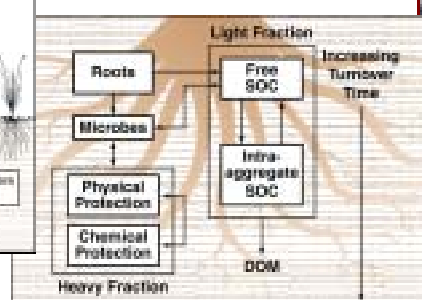
DOE National Environmental Research Park at Fermilab: Research site of opportunity

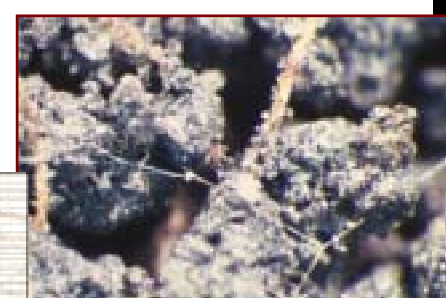
- Row-crop agriculture for ~150 y
- Chronosequence of prairie restorations initiated in 1975
- Prairie remnants
- Fields converted to Eurasian pasture grasses *c.*1971
- Woodlands
- Wetlands

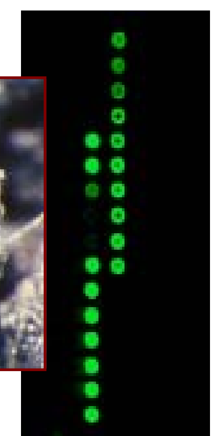
Multi-scale/multi-disciplinary studies at Fermilab

- Accrual of ecosystem C and N stocks
- Nitrogen controls on C accumulation
- Mechanisms controlling soil C stabilization
- Microbial biomass, diversity, function and activity
- Interfacial and molecular controls on humification
- Model parameterization and validation









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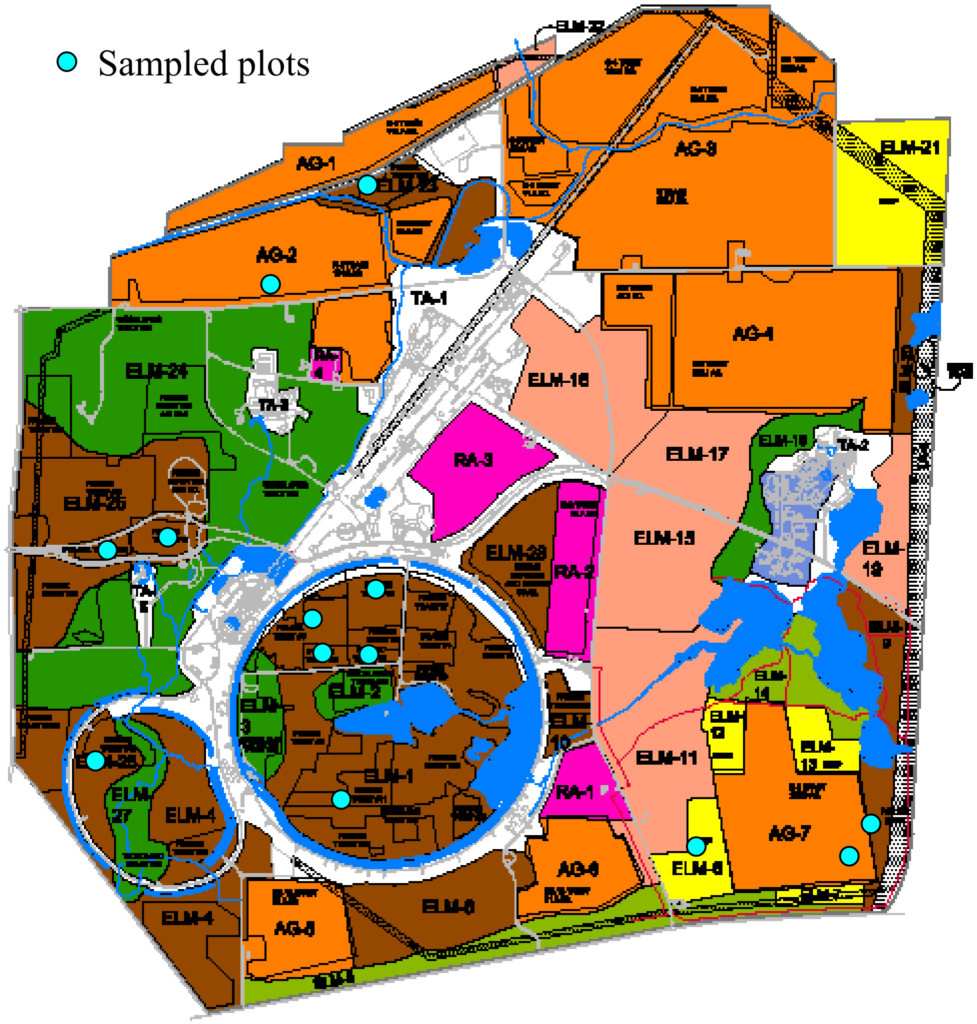
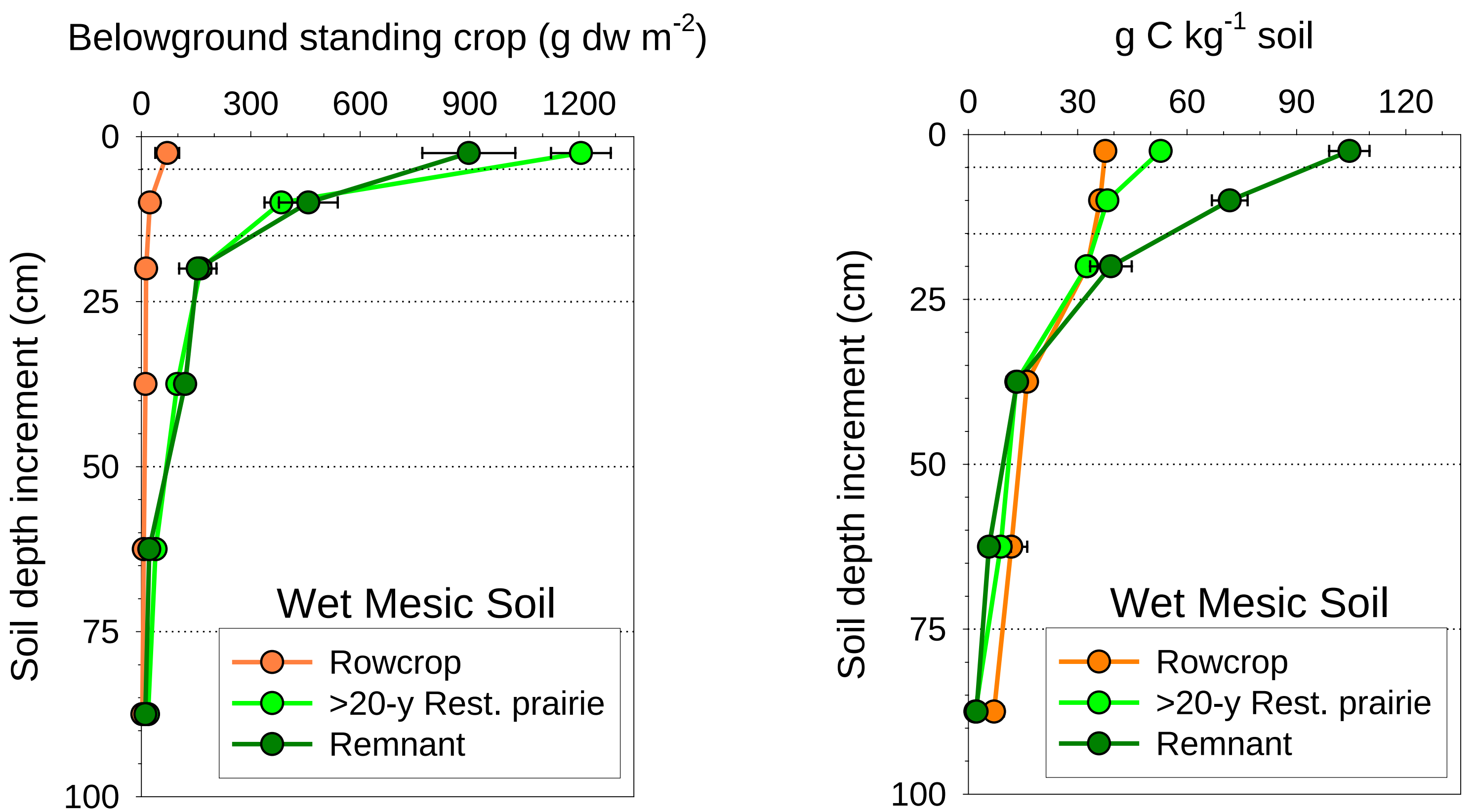
Fermilab chronosequence studies



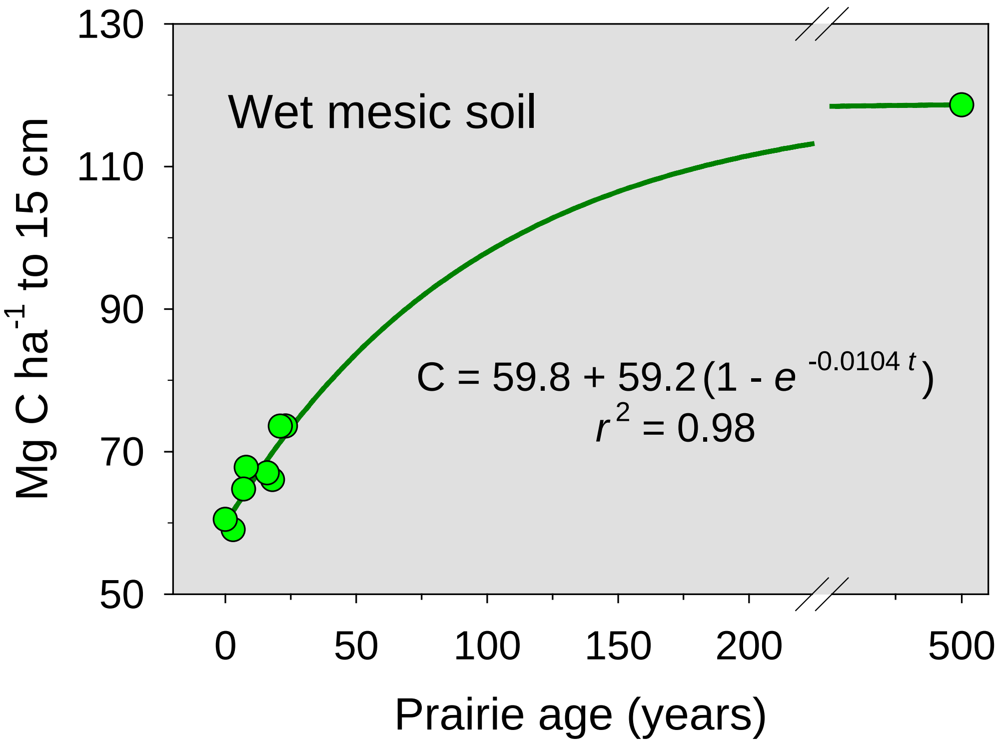
- ⇨ **Three soil types**
  - ➢ **Wet mesic,**
    Drummer silty clay loam
  - ➢ **Mesic,**
    Wauconda silt loam
  - ➢ **Dry mesic,**
    Barrington silt loam
- ⇨ **Chronosequence**
  - ➢ **2 Agricultural fields**
  - ➢ **9 Prairie restorations**
  - ➢ **1 Prairie remnant**
- ⇨ **Sample above- and belowground (1-meter depth)**

Depth distribution of inputs and soil C

- Belowground biomass in older restored prairies equals or exceeds remnants
- Root and rhizome inputs drive changes in soil C
- Greatest soil C increases in surface 5-10 cm
- Potential for long-term soil C accrual to 25-30 cm



Accrual of soil organic C sustained over 25 years



Based on equivalent soil mass for 0-15 cm depth at time zero

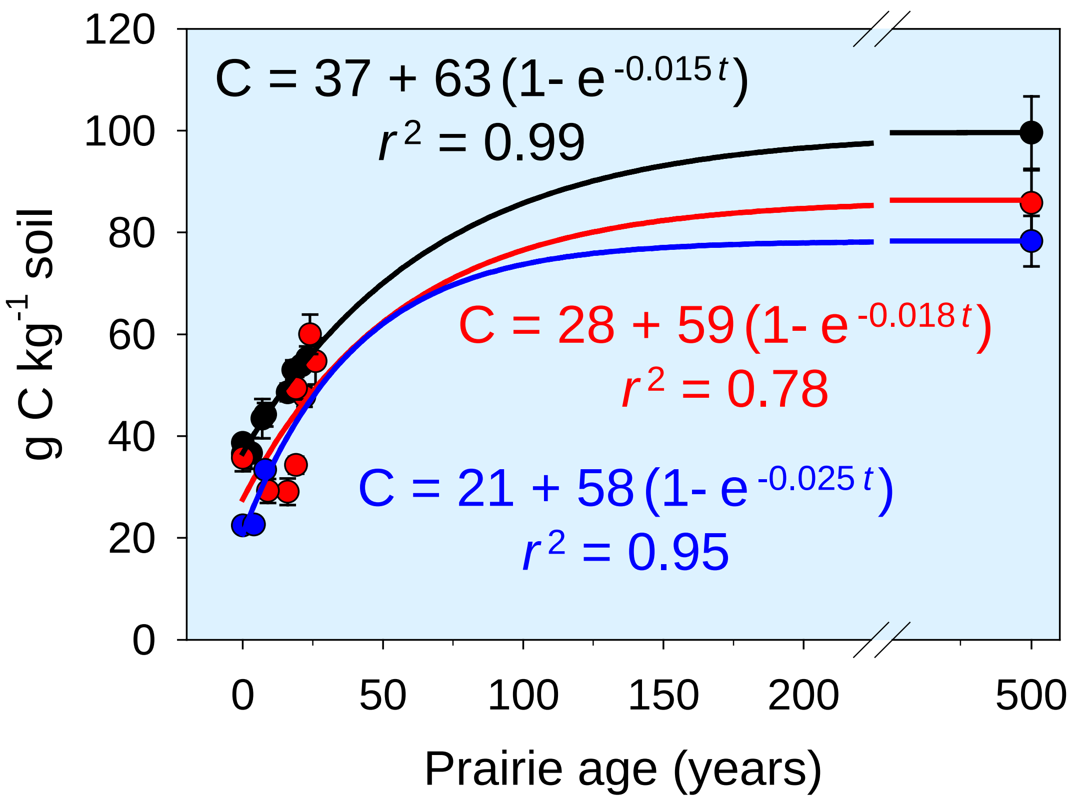
Exponential model predicts accrual of 0.54 Mg C ha^{-1} y^{-1} for 25 years in the surface 15 cm

C_e	118.6 Mg ha^{-1}
MRT	96 y
t_{50}	66 y

Effect of soil moisture/drainage conditions

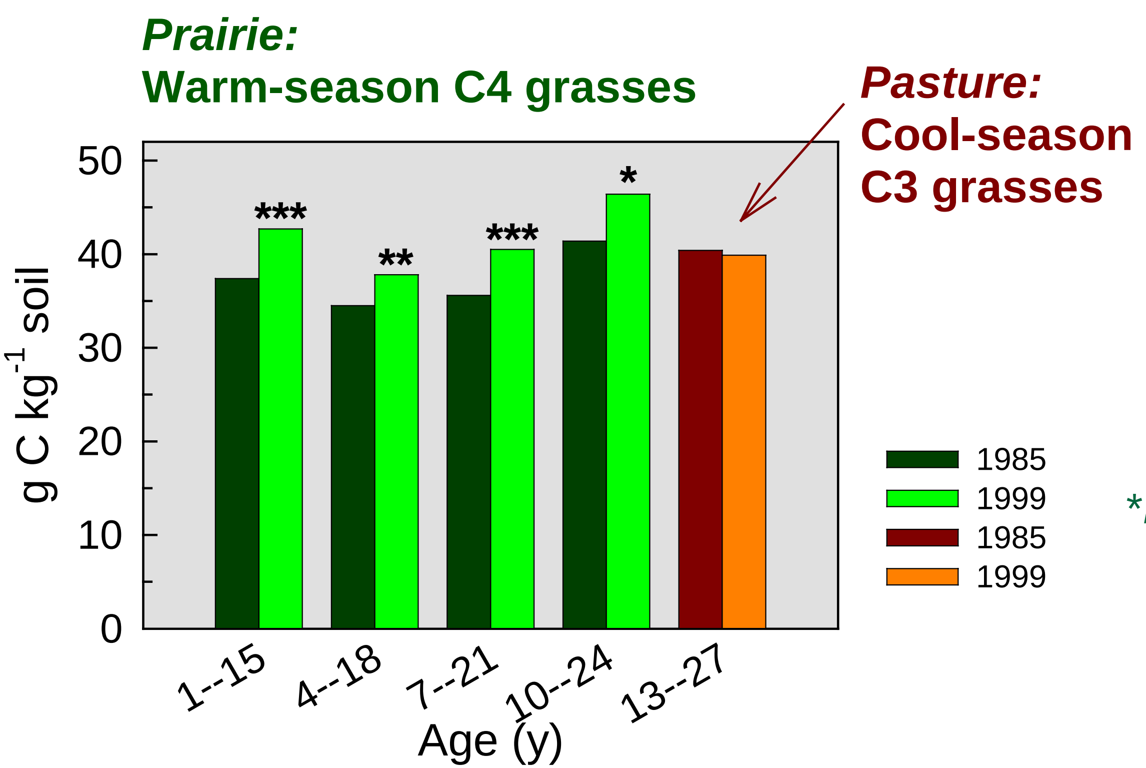
- Moisture affects equilibrium C for both disturbed and native
- Initial rates of C accrual are similar
- Time to equilibrium may vary

Protective capacity of these soils overcomes any differences in inputs



% of C_e accrued in 50 y	
Wet mesic	53
Mesic	59
Dry mesic	71

Grassland type influences soil C accrual



Repeated measure of marked sampling sites

*P < 0.05, **P < 0.01, ***P < 0.001
based on paired t tests.
0-10 cm depth

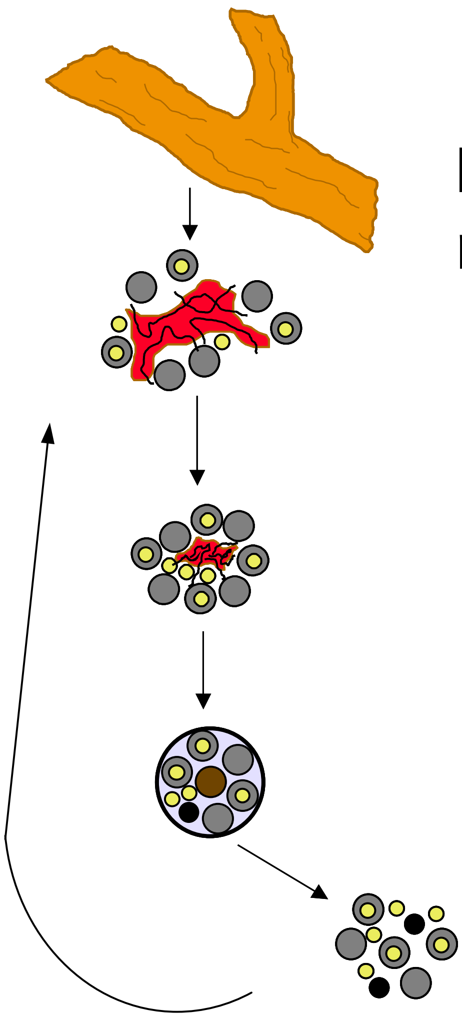
- Prairie increments verify modeled rates
- Pasture grasses at equilibrium by 13 years
  - Lower productivity (fertilizing might raise equilibrium)
  - Timing and quality of inputs affect decomposition

Changes in soil N cycling under restored prairie lead to accumulation of soil N

Site	Estimates based on ^{15}N pool dilution		
	Mineralization	NH_4 Consumption	Nitrification
	$\mu g\ N\ g^{-1}$ soil d^{-1}		
Row crop	22.2	17.5	14.7
8-y Prairie	11.6	9.5	0.1
22-y Prairie	4.3	9.7	0.3

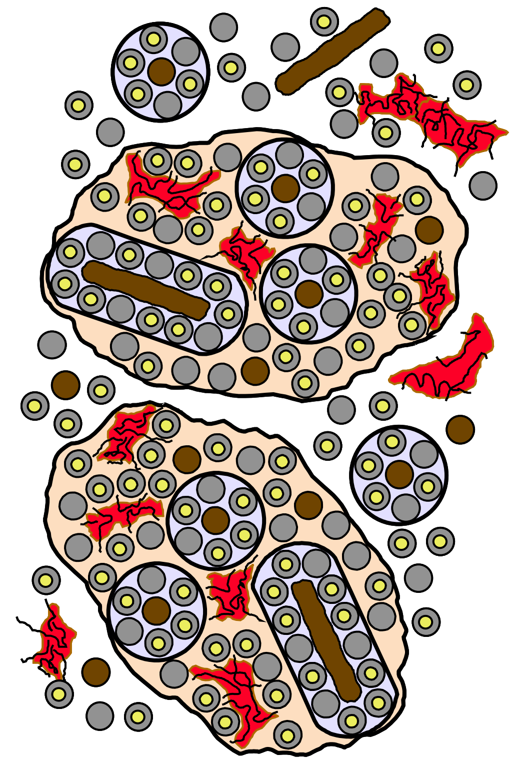
- N cycling most rapid in the agricultural soil
- Net N mineralization decreases with time in prairie
- Increased N retention and tighter N cycling
- N accrual sustains plant productivity and thus increases C storage

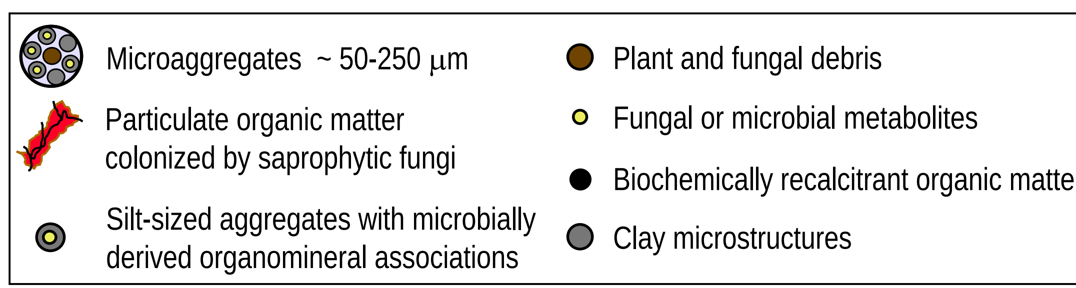
Conceptual models of soil C cycling and protection mechanisms used to develop new soil fractionations



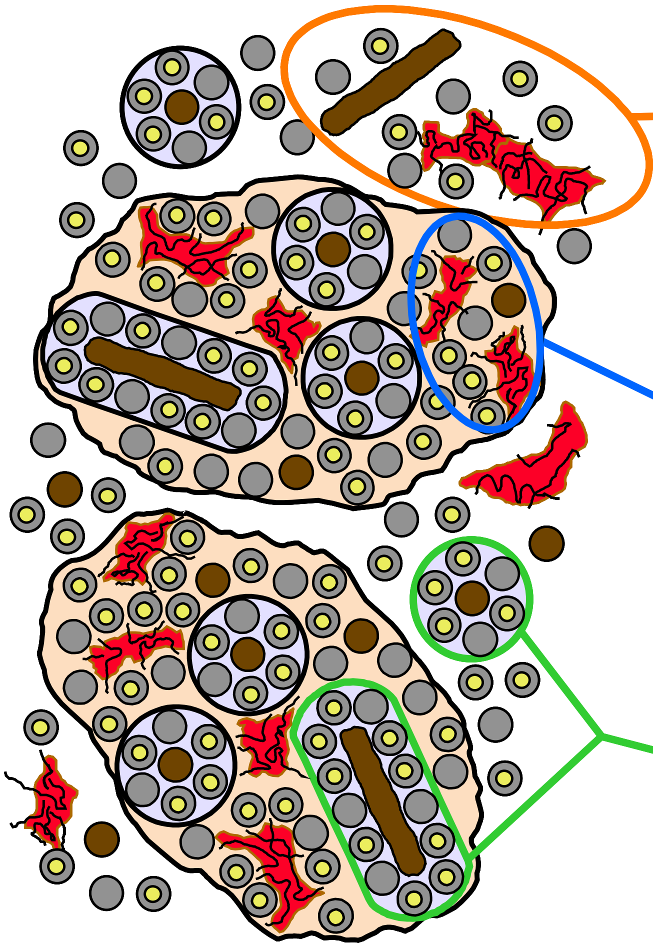
Incorporation into microaggregates:

- Physically protects organic inputs from decomposition
- Enables organic matter to be humified or chemically protected by association with the mineral fraction





Fractionation of Soil Organic Matter Based on Aggregate Hierarchy



Physical fractionation | ***Chemical fractionation***

Non-aggregated (NA)

Slaking
⇒ POM, silt & clay

→ **Acid hydrolysis** silt & clay

Macroaggregated (MA)

Microaggregate isolator
⇒ POM, silt & clay

→ **Acid hydrolysis** silt & clay

Microaggregated (mA)

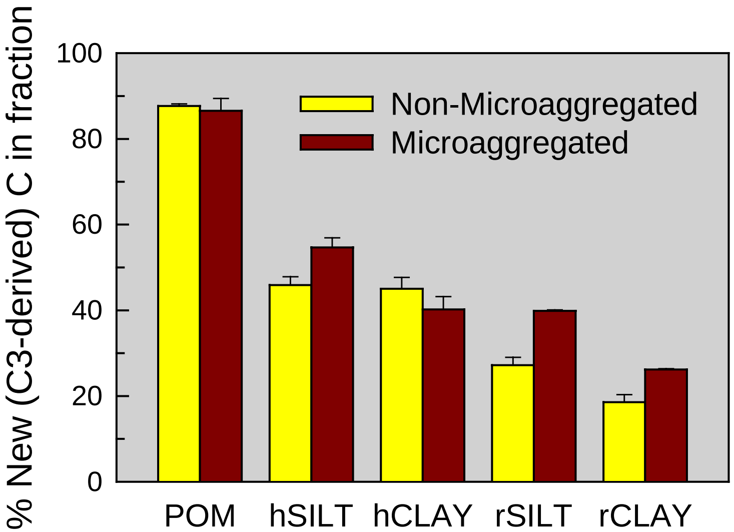
Dispersion
⇒ POM, silt & clay

→ **Acid hydrolysis** silt & clay

Based on increasing disruptive energies

Yields resistant and more labile fractions

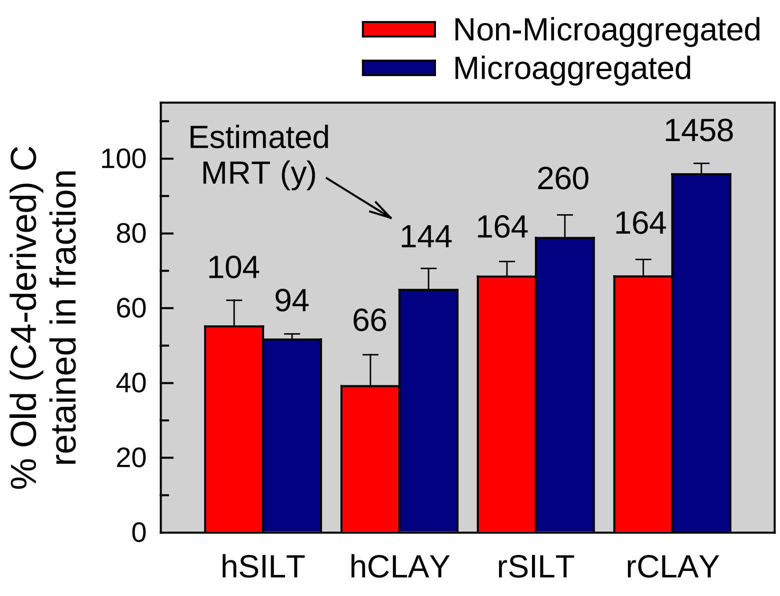
Mechanistic-based soil fractionations and stable isotopic tracers provide new insights to understanding C capture and storage



h = Hydrolyzable C
r = Chemically resistant C

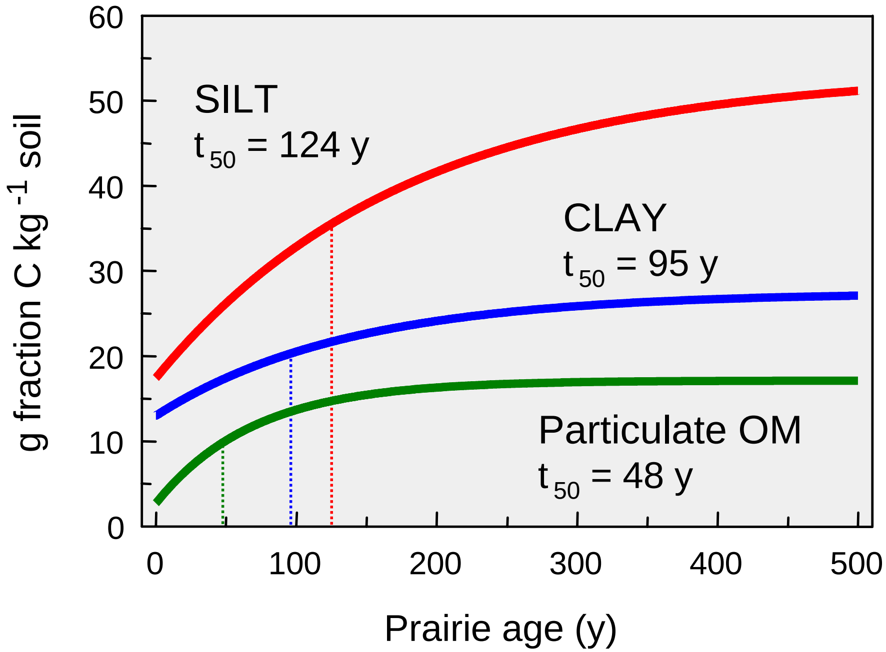
Microaggregates facilitate creation of organomineral associations (more new C in microaggregate-associated silt and clay)

Microaggregate protection increases the longevity of silt- and clay-associated C



h = Hydrolyzable C
r = Chemically resistant C

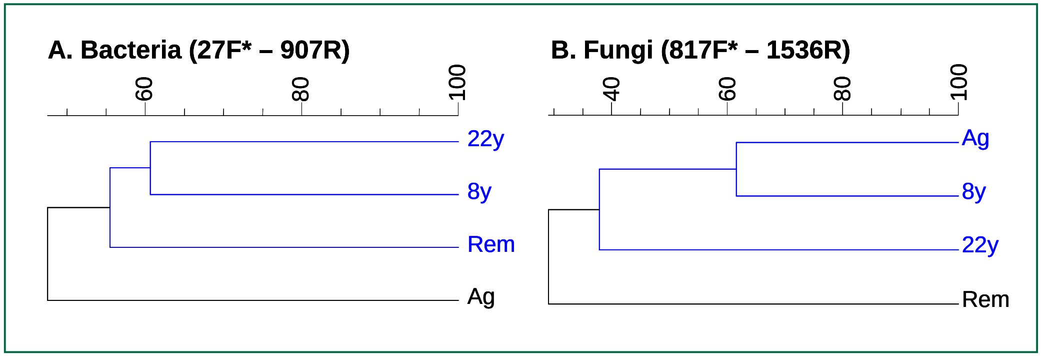
Rates of C accrual vary with particle size



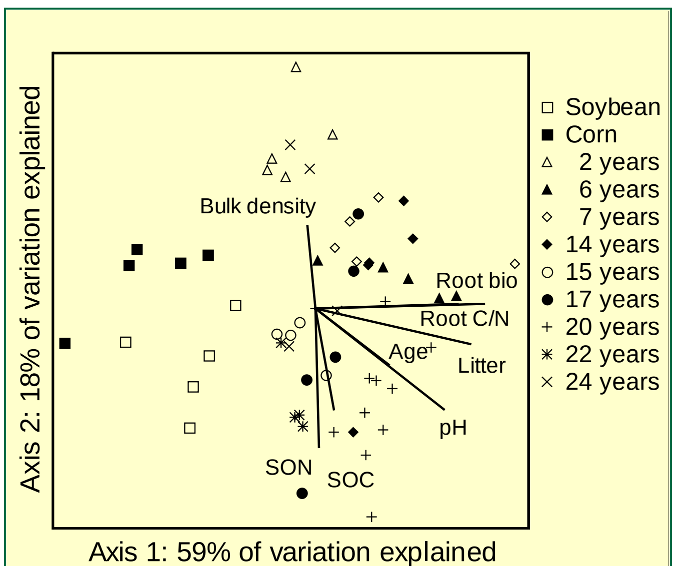
- Particulate OM reaches equilibrium first
- Largest increases in silt-sized fraction

- ~50% of silt-associated C is chemically resistant across the chronosequence
- Mineral-associated C has potential for entering longer lived pools

Plant inputs, quality, and manipulations associated with microbial changes



DNA fingerprinting shows bacterial community structures recover faster than fungal communities



PLFA analyses indicate:

- Changes in relative abundance of microbial functional groups are driven by plant inputs (amounts and quality) and related to changes in SOM and bulk density
- Fungal:bacterial ratios directly related to plant inputs
- Mycorrhizal fungi account for most of the increased fungal abundance

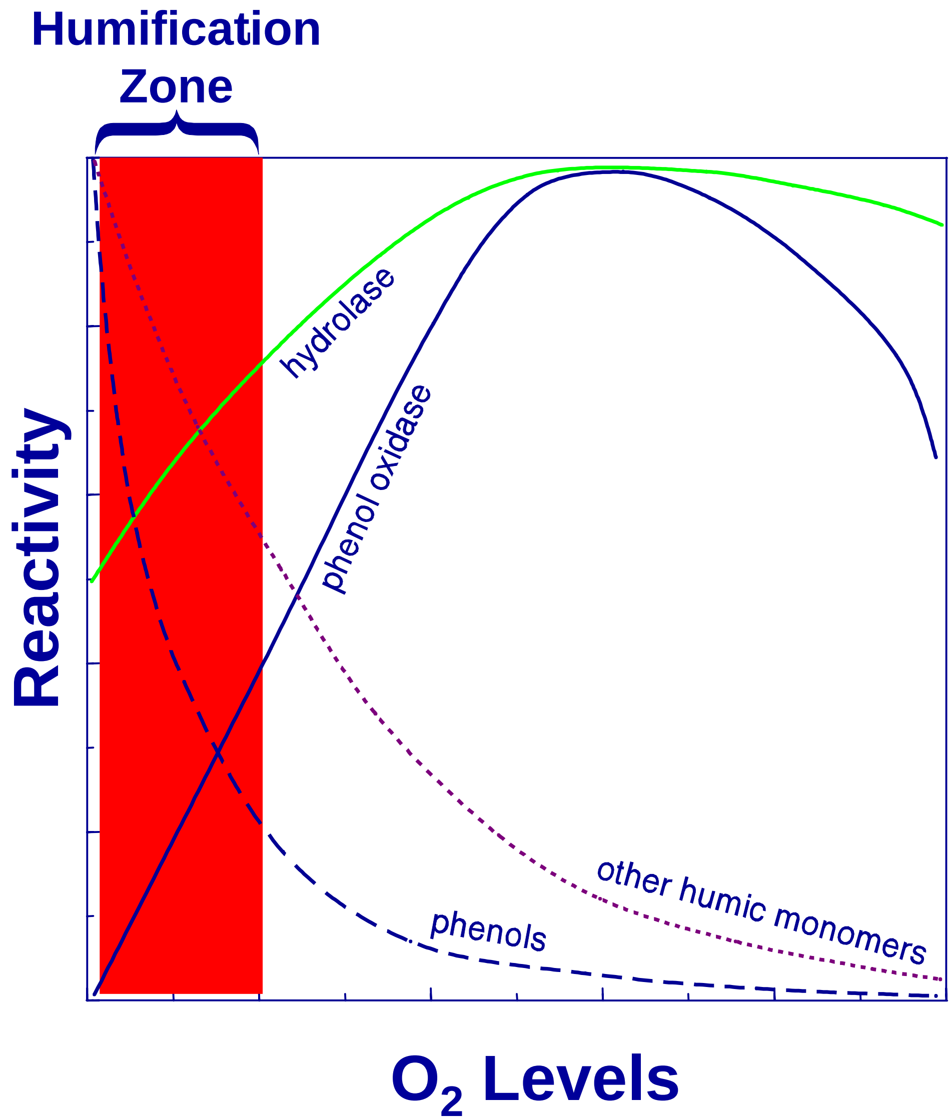
Increases in soil fungal:bacterial ratios and microbial diversity could increase the longevity of stored C

- Fungi use carbon more efficiently than bacteria (more C goes to biomass and less to respiration)
- Fungal cell walls are more difficult to decompose (e.g., chitin, melanin)

Managing plant communities or cultivars could effect micro-scale changes that may enhance sequestration

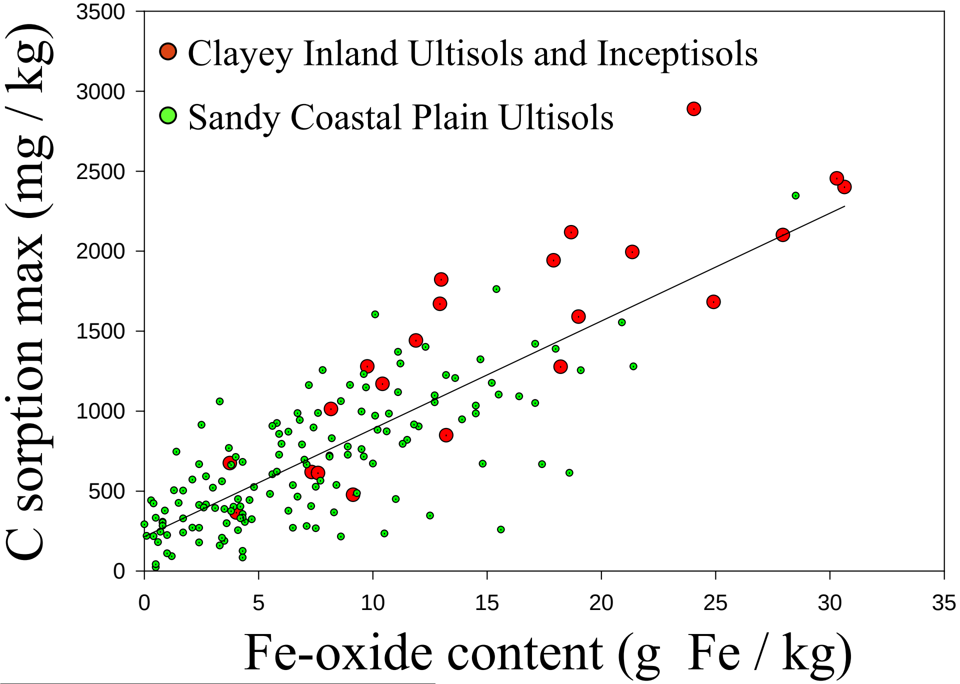
Can we optimize humification?
Sequestration in prairie soils provides clues

- Redox conditions
  - Wetting/drying cycles
  - Aggregation and roots density affect microsite conditions
- Fe/Mn oxide content
  - Fe/Mn nodules
  - Fertilization
- Enzyme activities
  - Roots with relatively high lignin contents
  - Green manuring
  - High fungal:bacterial ratios
  - Microaggregate pores may help stabilize enzymes



Emerging manipulation concepts:
Mobilization to deeper horizons

- Enhance hydrolysis of active organic C pools
- Conversion to passive organic C pools
- Amendments that promote deeper transport of C
- Approach
  - Regional soils
  - Lab-scale studies
  - Field-scale manipulation

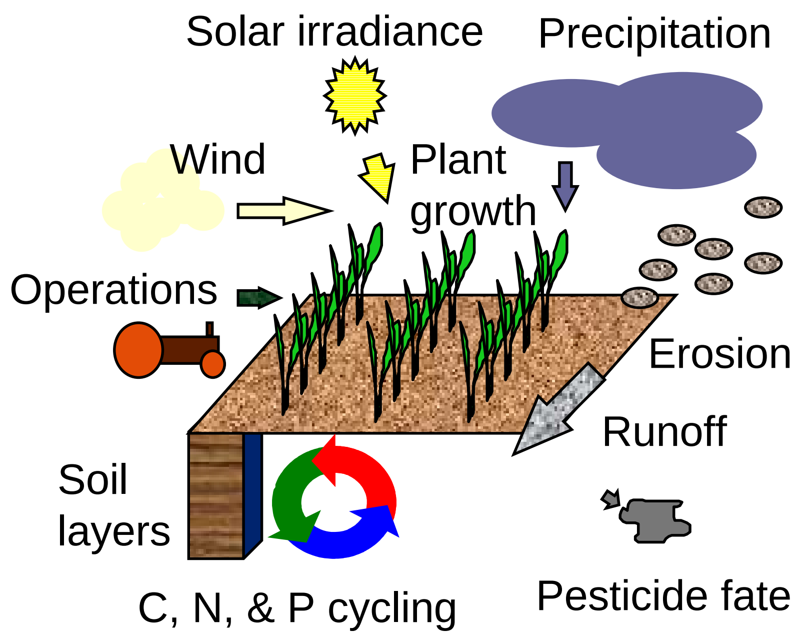


Where do we go from here?

- What is the nature, origin, and long-term stability of the C being accumulated in soils of different types?
- How do different management practices affect soil C accumulation and stabilization?
- What are the saturation limits for storing C in various soil types? What factors control these limits?
- Can we model measurable pools that are functionally meaningful and tied to processes?
- Manipulative experiments

Integrating soil and biological processes at landscape scale through simulation modeling

EPIC Model



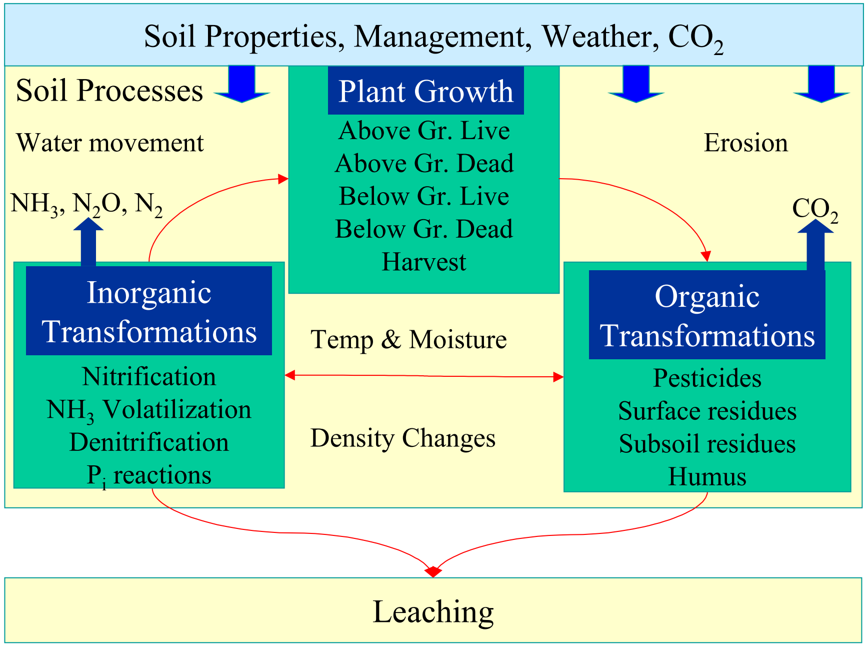
Representative EPIC modules

Williams (1995)

- **EPIC is a comprehensive model to describe climate-soil-management interactions at point or small watershed scales**
- **EPIC estimates the impacts of management on wind and water erosion**
- **CSiTE investigators recently updated C & N modules in EPIC (Izaurralde et al., 2001)**
- **CSiTE data could be used to improve applicability of the model for spatial and temporal extrapolation**
- **Combined with regional databases, this and other models (e.g., Century) can extend observations over conditions not directly measured**

Modeling soil C dynamics in a prairie restoration experiment at Fermilab

- The EPIC model was used to study soil C dynamics in prairie restoration experiment
- A 25-y weather record was assembled from Aurora, IL
- Crop parameters were adapted for modeling big bluestem growth
- Soil layer properties for the Drummer soil were obtained from STATSGO database and complemented with site information
- A 25-y run (1975 – 1999) simulated the conversion of an agricultural field to a pure stand of big bluestem
- N deposition was simulated at a rate of 2.1 mg/L (NADP)



Izaurralde et al. (2001)

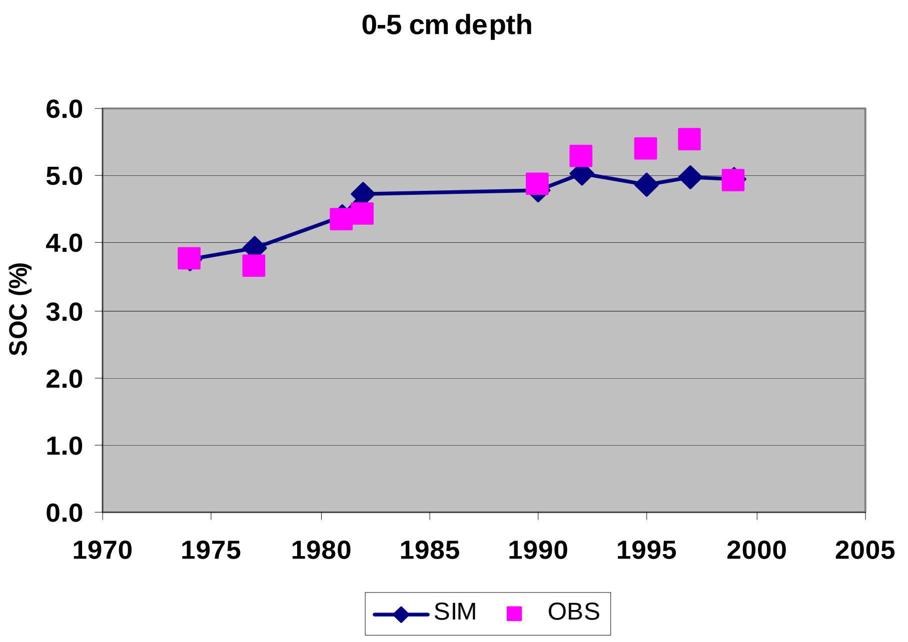
Simulated and observed average above and below ground big bluestem biomass (Mg/ha)

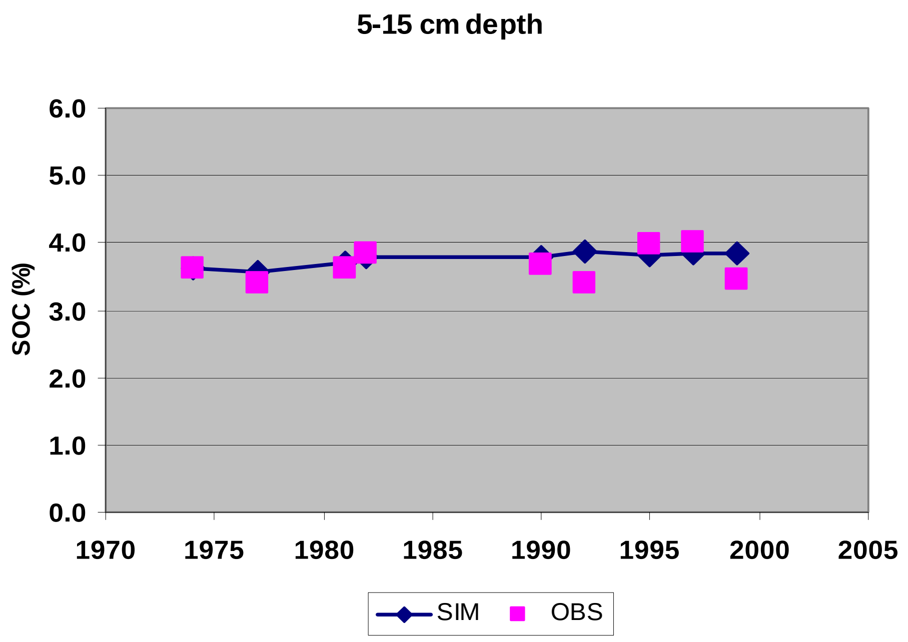
Andropogon gerardii

	Above ground biomass	Roots 0-5 cm	Roots 5-15 cm	Roots 15-25 cm	Root / Shoot ratio
Simu-lated	8.5	6.9	3.7	1.1	1.38
Obser-ved	8.3	9.0	3.1	1.8	1.67

Simulated and observed soil C (%) under big bluestem vegetation

- Overall, EPIC captured the soil organic C dynamics observed during 25 years in the Fermilab chronosequence experiment
- Most of the observed increase in soil C occurred in the top 5 cm soil depth
- The simulated annual rate of soil C accrual to 15 cm depth was lower than the one observed:
  - Simulated: 0.34 Mg/ha
  - Observed: 0.54 Mg/ha
- The under prediction of soil C by the model may be related to the under prediction of root and rhizome biomass in the top 5 cm soil depth





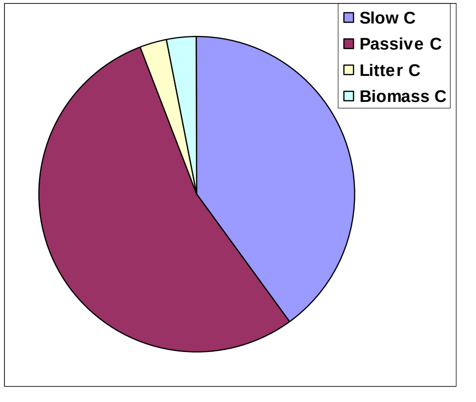
Initial and final soil microbial biomass C (%) in Fermilab chronosequence

	0-5 cm	5-15 cm	15-25 cm
Initial (1974)	1.0	1.0	1.0
Final (1999) Simulated	3.2	2.7	2.6
Final (1999) Observed	3.1	2.7	2.5

Credit: R. Campbell. 1985. Plant Microbiology. Edward Arnold, London. p. 149.

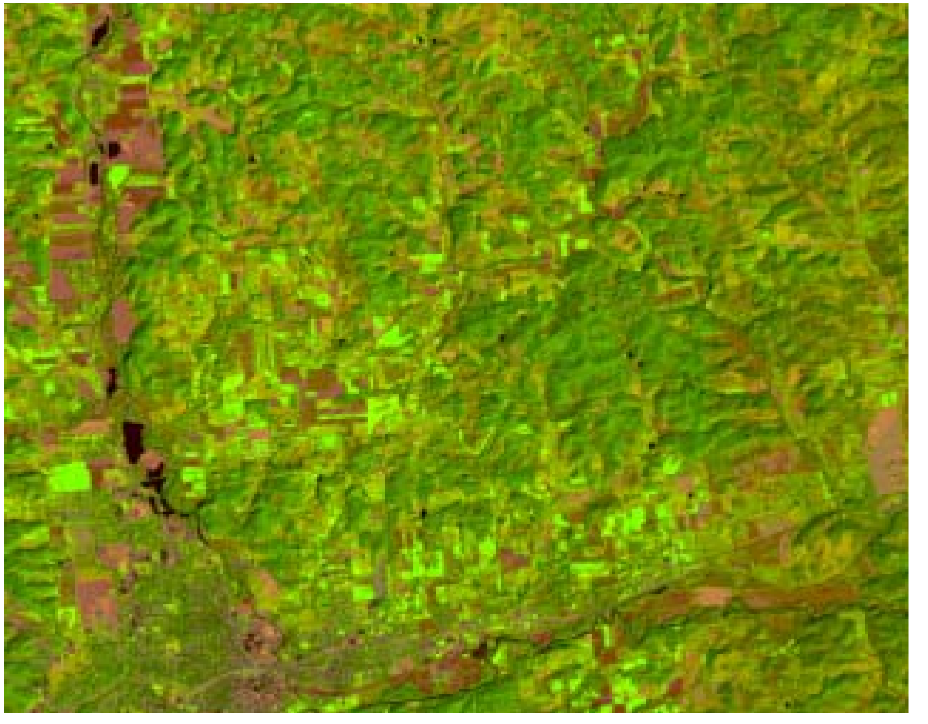
Distribution of C within soil C pools

- Passive C represented ~54% of the total
- Most of the C accrual occurred in the slow C pool



Using Model Results to Calculate Regional Soil C Sequestration

- Data from Coshocton and Fermilab and simulation modeling allow estimating
  - C sequestration potential over time
  - C in eroded sediments
- The model can be used to extrapolate to regional edaphic and management conditions
  - Multi-field version of EPIC
- Capability to simulate non-CO_2 gases (e.g. N_2O) will be available in near future



Land use pattern in NAEW region:

Forests, meadows and cropland

Integration for Regional Carbon Sequestration Evaluation

Need for an Integrated Approach

- Agricultural, silvicultural, and land-use management for C sequestration will be adopted only if:
  - Amount, capacity, and longevity are known,
  - Net reductions in greenhouse gases occurs,
  - Methods are environmentally beneficial, and
  - Economic aspects are attractive.
- Science methods need development to take discoveries in C sequestration at the plot scale to perform regional scale environmental and economic analyses.

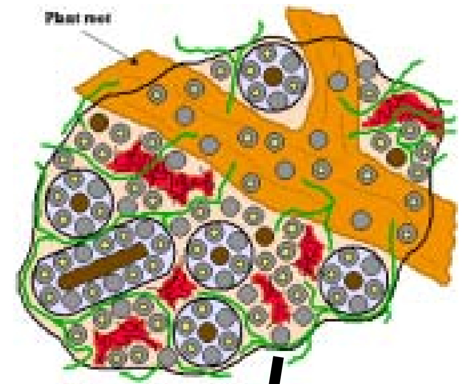
Integrated Approach to Evaluating Terrestrial C Sequestration

CSiTE is developing an approach that involves:

1. **Identification of promising technologies**
2. **Understanding basic mechanisms**
3. **Performance of sensitivity analysis**
4. **Inclusion of full C and GHG accounting**
5. **Evaluation of environmental effects**
6. **Performance of economic analysis**

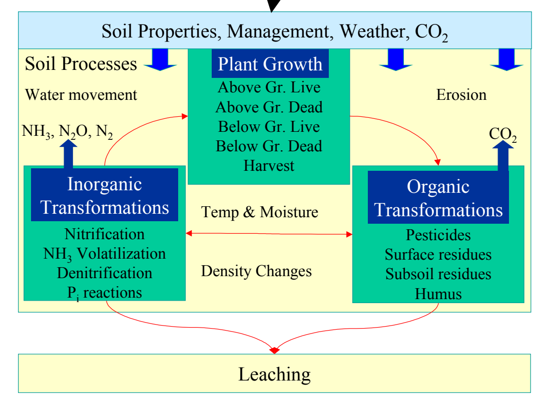
1. Identification of Promising Technologies

- Analysis of sequestration in existing practices.
- Identification and testing of novel manipulations.



2. Understand Controls and Basic Mechanisms

- Edaphic, biological, and environmental conditions.
- Physical protection, biochemical recalcitrance, chemical protection.

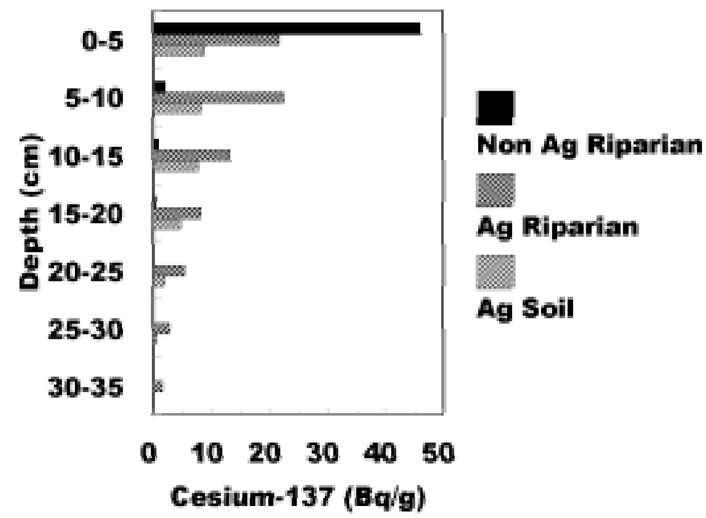


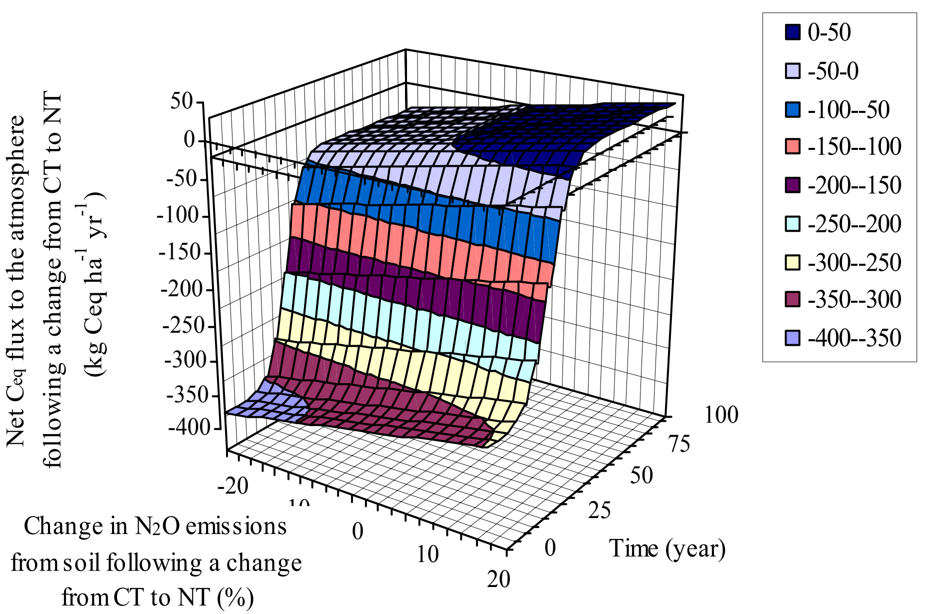
3. Perform Sensitivity Analysis for Spatial and Temporal Extrapolation

- Models generalize experimental results.
- Use models and GIS data calculate sequestration.

4. Inclusion of Full C and GHG Accounting

- Include net GHG emissions for all components of management.



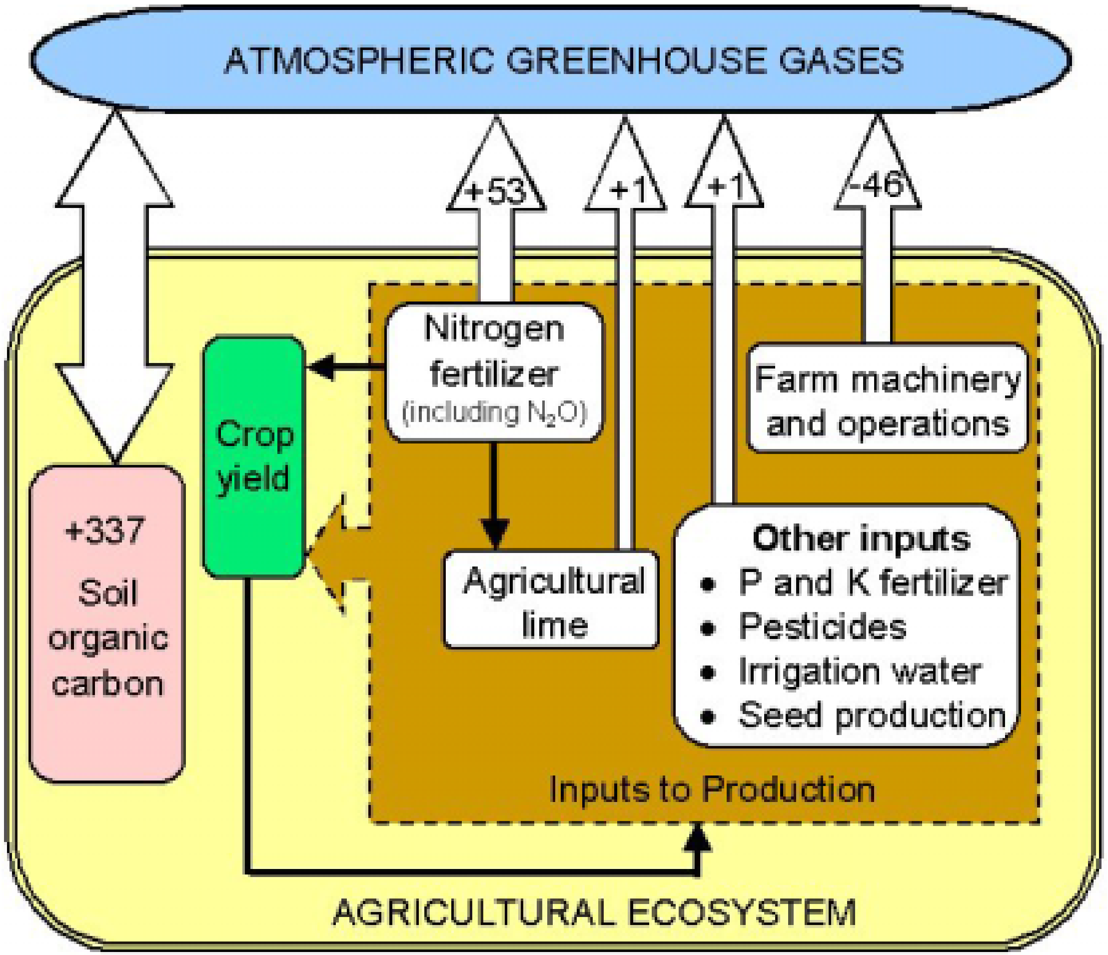


5. Evaluation of Environmental Effects

- Erosion control, water quality
- Biodiversity

Model analysis of full CO_2 and greenhouse gas accounting

- **Agriculture**
  - Tillage
  - Fuel
  - Fertilizer/pesticides
  - Lime, seeds
  - N_2O, CH_4
- **Forest harvest**
  - Forest growth, age
  - Harvest operations
  - Fate of wood products



West, T.O. and G. Marland. 2002. Environ. Pollution 116:437-442.

6. Perform Economic Analyses

- For a management practice to be adopted it must be:
  - Cost effective
  - Involve tolerable amounts of risk
  - Have a market (economic) method or a fair governmental (social) method of implementation
- Economic models require a cost per ton calculation
- Cost per ton should include:
  - Net cost of practice, amount of GHG offset
  - Producer development cost, adoption inducement cost
  - Market transaction costs, governmental costs
  - Discounts
  - Value of co-benefits

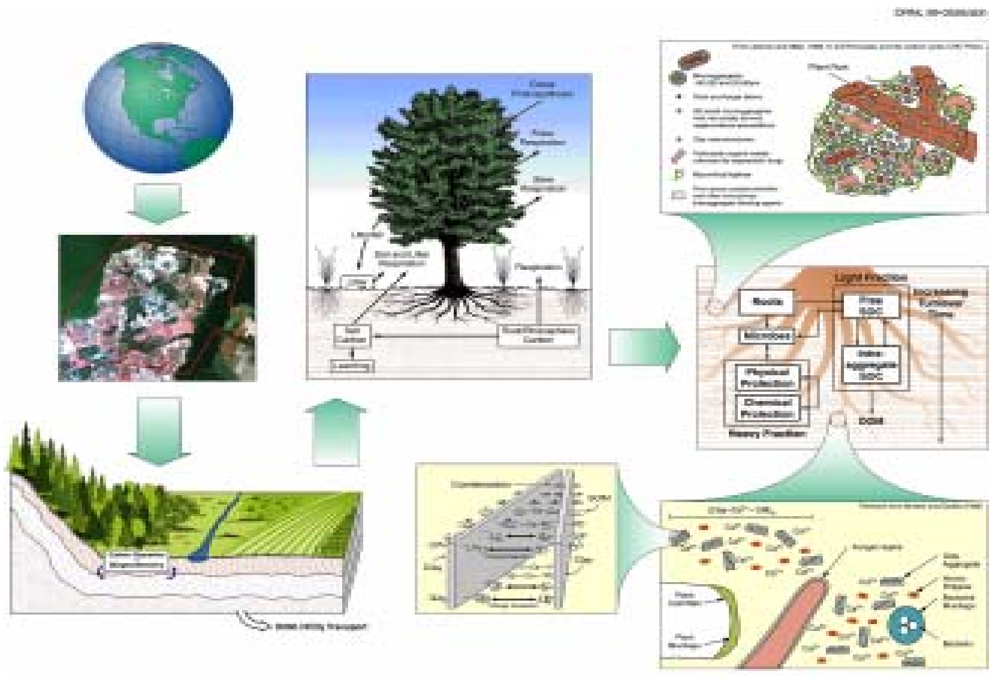
$$\text{Cost per ton} = \frac{\text{net cost of practice}}{\text{amount of GHG offset}}$$

$$\text{Private cost per ton} = \frac{(PDC + PAIC + MTC - GC)}{\Delta GHGO * (1 - DISC)}$$

$$\text{Social cost per ton} = \frac{(PDC + PAIC + MTC + \varphi * GC - CB)}{\Delta GHGO * (1 - DISC)}$$

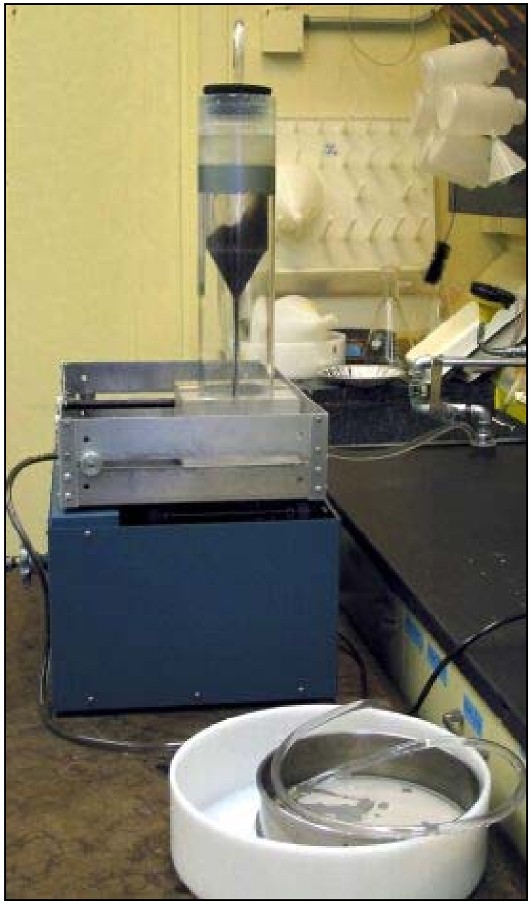
Future CSiTE Directions

- **Continue**
  - **Multi-scale/multi-disciplinary research**
  - **Model development & landscape extrapolations**
- **Explore**
  - **New manipulations**
  - **Regional analyses**

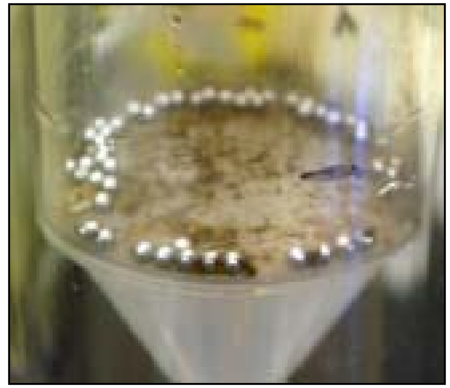


Questions ?

Soil Fractionation with Microaggregate Isolator



Microaggregate isolator



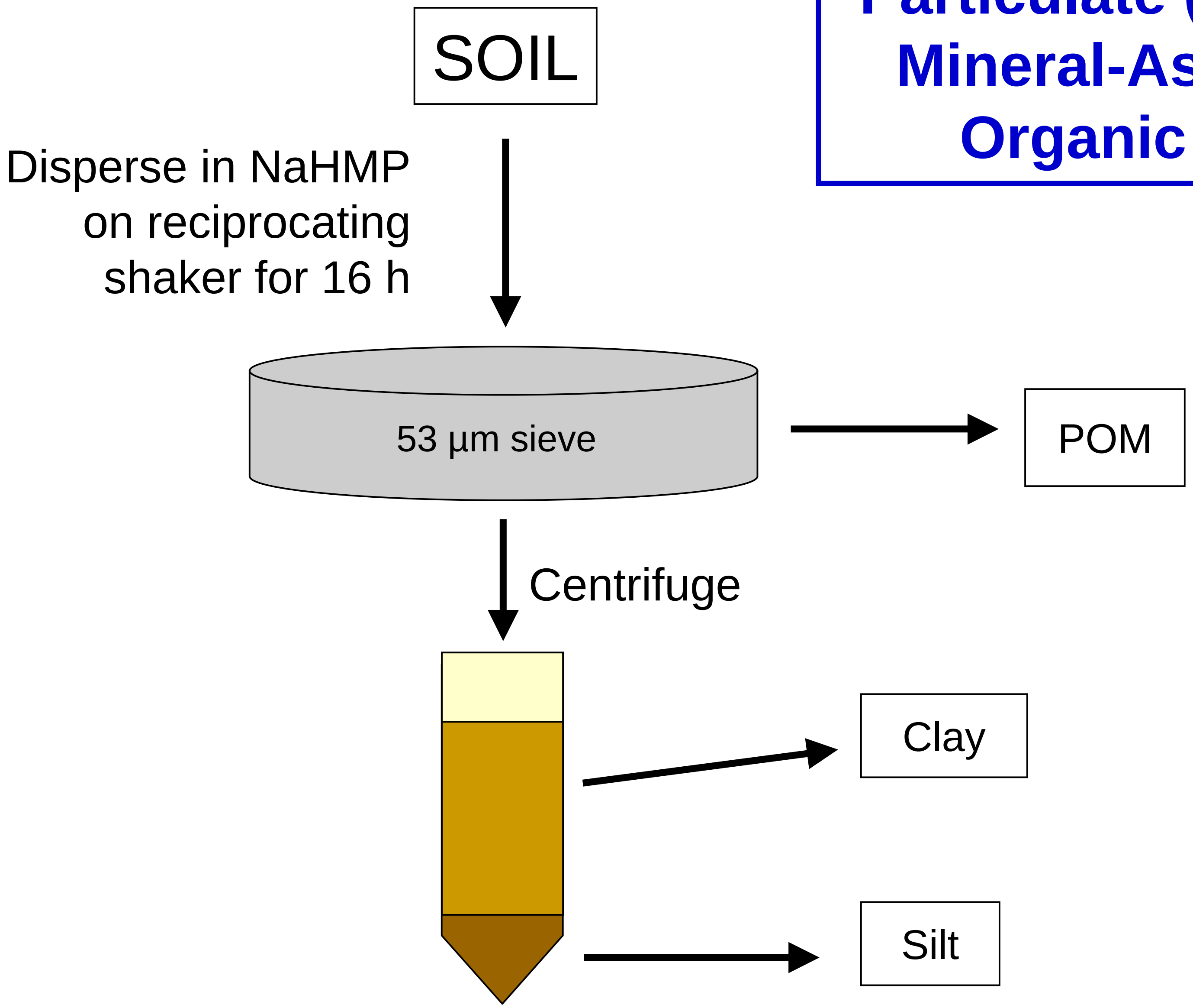
Unprotected coarse POM

Unprotected fine POM

Microaggregates

Silt & clay

Fractionation of Particulate (POM) and Mineral-Associated Organic Matter



Enhancing Carbon Sequestration – *"Reality"*

- **External C balance must be quantified**
  - Fertilization, irrigation, transportation
- **Other greenhouse gases must be evaluated**
  - CH_4, N_2O
- **Changing climatic factors must be considered**
  - Afforestation reducing albedo – leading to warming
- **Environmental impacts must be assessed**
  - Biodiversity, water pollution, soil erosion
- **Economic and social drivers must be accounted**
  - Trade-offs related to land-use changes emphasizing C storage
    vs. other ecosystem goods and services

Enhancing Carbon Sequestration in Terrestrial Ecosystems – *The Bottom Line*

- **Increase Belowground Carbon**
  - Longevity of soil carbon
  - Depth of soil carbon
  - Density of soil carbon
  - Root mass (longevity and amount**)**
- **Increase Aboveground Carbon**
  - Accumulation rate
  - Productivity or C density
  - Longevity
  - Long-term use or storage
- **Optimize Land Use**
  - Social, economic, ecosystem issues